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INTEGRATION OF HEAT PUMP IN COMBINED HEAT AND POWER PLANT – COMPARISON OF VAPOR COMPRESSION AND ABSORPTION TECHNOLOGY

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ABSTRACT

A central combined heat and power plant based on extraction steam turbines may operate in a range of modes. The operating map is defined by boiler load and maximum (back-pressure mode) to zero (condensation mode) heat production. The paper investigates the potential of expanding the map by integrating a heat pump in the cycle of the Avedøreværket Power Station in Copenhagen to preheat the return of district heating. The analysis was made for both vapor compression or absorption technology by numerical simulations of the plant. In both cases power was sacrificed to produce heat. For the vapor compression heat pump electricity from the generator was consumed, while for the absorption unit low pressure steam was used for the heat pump generator instead of producing power. Both heat pumps extend the heating capacity of the plant. The vapor compression unit produced 85.9 MJ s^{-1} additional heat while sacrificing 17.1 MW power. The absorption heat pump produced 74.5 MJ s^{-1} heat at a COP of 1.75, while sacrificing 8.9 MW power. Hence the compression heat pump produced a higher amount of heat, while the absorption heat pump provided a little better electric and exergy efficiency. In addition to the better performance of the absorption heat pump, its lower investment meant that it was estimated to have a payback period of 8.6 years compared to 16.8 years for vapor compression unit.

Keywords: Vapor Compression Heat Pump, Absorption Heat Pump, Combined Heat and Power, Energy utilization, Exergy analysis

1. INTRODUCTION

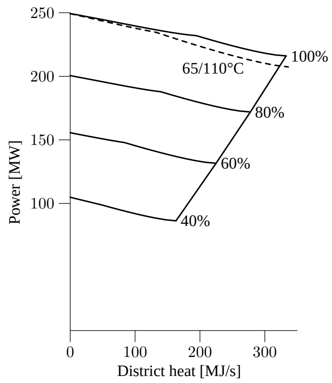
Cogeneration in Combined heat and power (CHP) plants is a an important technology in the Danish district heating sector (Danish Energy Agency (2017)). District heating supplies 63 % of the dwellings and cogeneration covered 67% of the heat supply for district heating in 2015.

In cities the main part of the heat is generated at central CHP units, e.g., the Avedøre Power Station illustrated in figure 1(a). The plant consists of two individual units, each being a combined heat and power unit based on extraction steam turbines. Figure 2 illustrates the process diagram of the Unit 1 (AVV1) of the plant operating in the full back-pressure mode based on the results of a validated model presented in Elmegaard and Houbak (2003).

The unit may operate in a range of modes. The operating map, often illustrated in form of a power-heat diagram as presented in figure 1(b), is defined by minimum to maximum boiler load and zero to maximum heat production. At zero heat production the plant is operating in *condensation mode*, which may be changed to full heat production in *back-pressure mode* by changing the positions of valves V1a, V1b, V2a and V2b to allow steam to bypass the low-pressure turbine stages and instead condense in the district heating heat exchangers.

The basic idea of CHP is to produce heat as byproduct of the power production. Hence, it is produced at high efficiency and at low price. Applying this approach the CHP plant may be seen as a virtual heat pump that produces heat by sacrificing electric output (Lowe (2011)). The AVV1 unit produces 249.3 MW power at an electrical efficiency of 35.9 % in condensing mode. The turbine inlet conditions are 240 bar/540 °C and the sea water cooled condenser works at 30 °C. At full back-pressure it produces 216.0 MW power and 332.9 MJ s^{-1} district heat for the primary network in Copenhagen at a forward temperature of 100 °C and a return temperature

(a) Photo showing CHP units and heat storages



(b) Operating diagram of Avedøreværket Unit 1 from Elmegaard and Houbak (2003)

Figure 1. Avedøre Power Station, Copenhagen, Denmark

of 50 °C. Accordingly, 33.3 MW power is sacrificed and the apparent Coefficient of Performance (COP) of the plant seen as a virtual heat pump is 10.0. However, in the present Danish energy system, power is generated based on wind turbines to large extent, both on average and in individual hours. This makes it challenging for CHP units to be competitive in the electricity market, which causes a dilemma due to the requirement of providing heat to the heat consumers. Hence, it may be beneficial to expand the heat production by sacrificing additional power.

The operating map may be expanded by integrating a heat pump in the cycle to heat the return water to the forward temperatures of the district heating network. The heat pump may be either vapor compression or absorption technology. In both cases the high-exergy source for the heat pump is low pressure steam, which may either expand through the turbine to produce power for the heat pump compressor or be used as driving heat for the absorption cycle.

Integration based on absorption heat pumps is presently in operation in Copenhagen. Two examples of such are the Amagerværket unit which is presently integrated with an absorption heat pump that utilizes heat from a geothermal source at 73 °C to produce heat at 85 °C, which is further boosted to reach district heating forward temperature (Dansk Fjernvarme). The Vestforbrændingen Waste incineration plant uses flue gas as the heat source for the heat pump (Clausen et al. (2014)). Examples of other uses of integration of absorption heat pumps with power plants are e.g., integration with a combined cycle-based CHP unit (Lickrastina et al. (2014)) and with a geothermal power plant (Nowak et al. (2008)).

The paper investigates the options of integrating a vapor compresion heat pump or an absorption heat pump into a large-scale CHP located in Copenhagen, Denmark. The solutions are based on energy, exergy and economic assessment.

2. METHODS

The model of the AVV1 unit presented in Elmegaard and Houbak (2003) was implemented in DNA (Elmegaard and Houbak (2005); Pierobon et al. (2014)). It includes the complete plant in the full operating map from minimum technical load of 40 % to full boiler capacity and from zero to full district heating production, accounting for the variations of the characteristics of the different components. Properties of steam were calculated based on Wagner and Kruse (1998). Properties of LiBr-water solutions were determined by the fomulations of Pátek and Klomfar (2006).

The model was further extended to include a vapor compression heat pump driven by electricity generated by the plant and an absorption heat pump driven by extraction steam from the low pressure stages of the turbine in Kaniadakis (2014) and Villegas Martínez (2015). Because the intention is to expand the capacity for heat production of the plant, the relevant part of the operating map is the back-pressure line where the plant is already at full heat production. In this mode, valves V1a and V1b are fully open, and V2a and V2b are almost closed only allowing steam flow for cooling the low pressure turbines.

The heat pumps were assumed to increase the temperature of the return district heating water temperature by

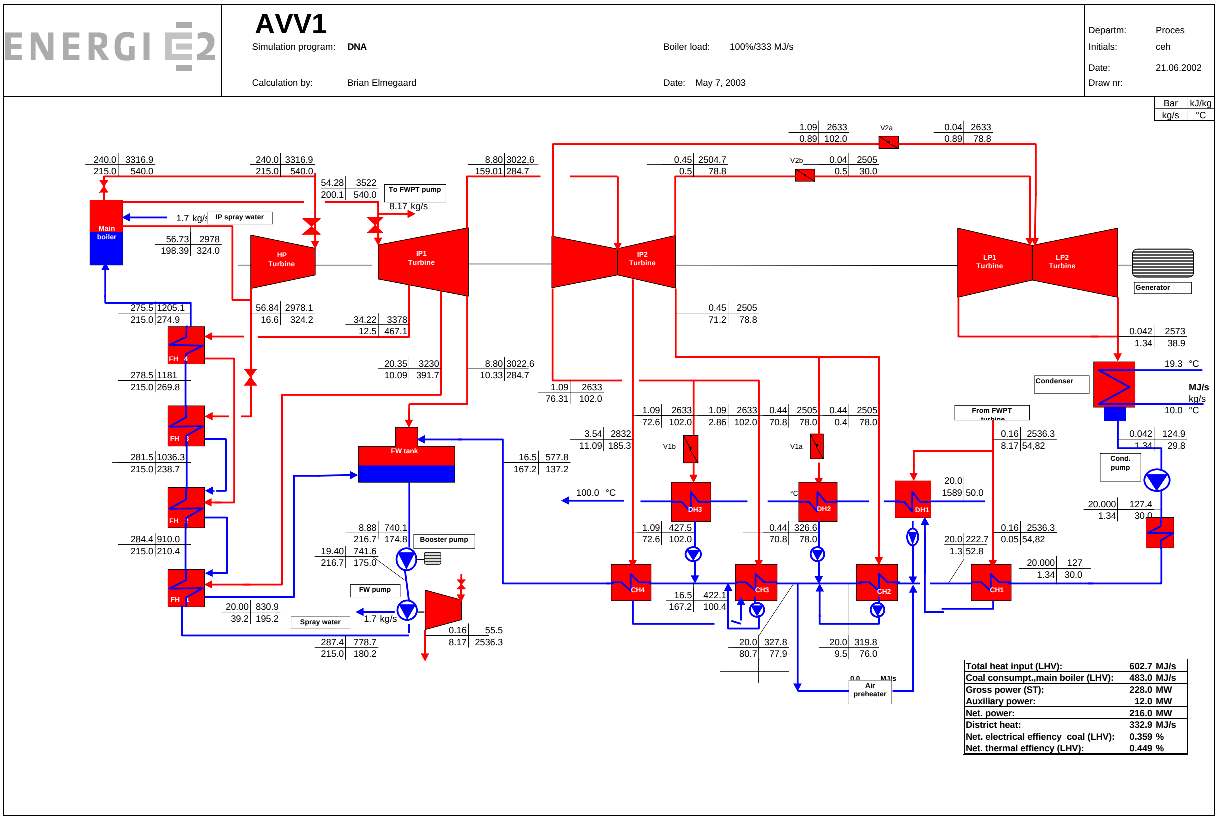
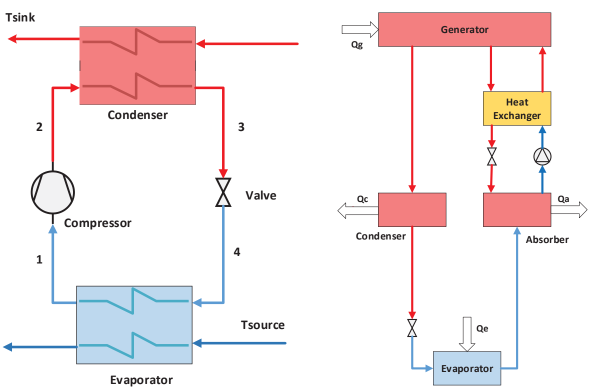


Figure 2. Avedøreværket Unit 1 Process Diagram from Elmegaard and Houbak (2003)



(a) Vapor Compression Heat Pump

(b) Absorption Heat Pump

Figure 3. Diagrams of heat pumps

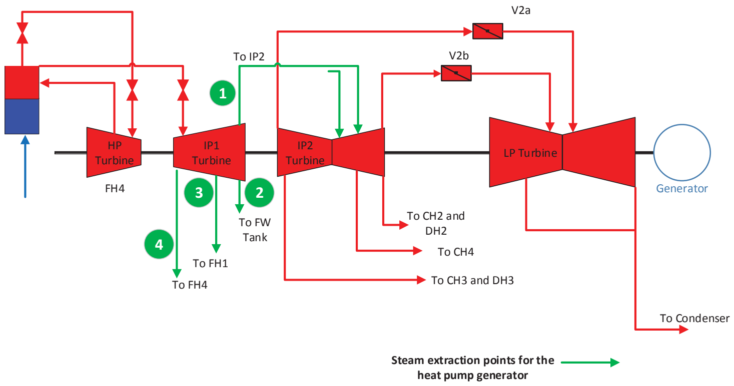


Figure 4. Extraction points for driving steam for absorption heat pump

10 °C to avoid to drastic changes of the district heating part of the plant, which is already operating at full back pressure mode to reach the highest possible heat production (Ommen et al. (2014)).

2.1. Vapor Compression Heat Pump

The vapor compression unit illustrated in Figure 3(a) was assumed to be based on large-scale ammonia units serially connected on the district heating side to reach high Coefficient of Performance and capacity. A heat source of 40 °C was assumed to allow an evaporator temperature of 30 °C. The condenser also operated at 10 K minimum temperature difference to reach a condenser temperature of up to 70 °C depending on the temperature glide. Superheating and subcooling were assumed to be 0 K. For the compressor the isentropic efficiency was assumed to be 70 % and the mechanical efficiency of motor and drive to be 90 %. Pressure loss was neglected in the heat pump cycle.

The Coefficient of Performance of the heat pump, COP, was defined as:

$$\mathrm{COP} = \frac{\dot{Q}_{\mathrm{cond}}}{\dot{W}_{\mathrm{comp}}} \tag{1}$$

2.2. Absorption heat pump

The model of the absorption heat pump as illustrated in Figure 3(b) was based on a LiBr-H_2O unit using extraction steam as driving heat for the generator. Based on analyses of the plant operation and options for additional steam extraction for driving heat for the heat pump, it was found that steam should be extracted from the intermediate pressure turbine IP1. Four options for extraction were available as illustrated in Figure 4. To reach reasonable operating conditions in the absorption cycle, and to be able utilize both the condenser heat and the absorber heat from the heat pump, it was required to obtain sufficiently high temperatures in both these units for heating the district heating return. The evaporator temperature was assumed to be 60 °C, while the condenser and absorber temperatures were both assumed to be 90 °C. As a reasonable match between the temperature of the extraction steam and of the generator demands, the generator temperature was assumed to be 150 °C. The solution leaving the both the absorber and generator were assumed to be at equilibrium with the water vapor in the unit.

The Coefficient of Performance of the heat pump, COP, was defined as:

$$\mathrm{COP} = \frac{\dot{Q}_{\mathrm{cond}} + \dot{Q}_{\mathrm{abs}}}{\dot{Q}_{\mathrm{gen}}} \tag{2}$$

2.3. Evaluation Criteria

Due to the fundamental differences between the two heat pump technologies, it is not directly possible to compare the coefficient of performance. In addition, the heat pumps are in this case integrated into a complex steam power cycle and the performance of the system depends both on the power production and the heat production. For this reason other criteria for the evaluation of the solutions should be applied.

The electrical efficiency of the power production is significant for illustrating the consequence of sacrificing power to produce additional district heating. The electrical efficiency of the plant is defined by

$$\eta_{\text{el}} = \frac{\dot{W}_{\text{net}}}{\dot{Q}_{\text{boiler}}} \tag{3}$$

Often the performance of combined production is quantified by the energy utilization given as

$$\epsilon = \frac{\dot{W}_{\text{net}} + \dot{Q}_{\text{dh}}}{\dot{Q}_{\text{boiler}}} \tag{4}$$

But an energy-based comparison of power and heat does provide full insight in the performance from the viewpoint of thermodynamics. In addition, the utilization of the exergy input in terms of chemical exergy of the fuel may be evaluated and used to compare the performance. In this case the fuel exergy is constant, and the performance may be illustrated by the exergy destruction of individual components and the complete system. For the system the exergy destruction is given by

$$\dot{E}_{\text{dest}} = \dot{E}_{\text{boiler}} - \left(\dot{E}_{\text{Power}} + \dot{E}_{\text{dh}}\right) = \dot{E}_{\text{boiler}}\left(1 - \eta_{ex}\right), \tag{5}$$

where η_{ex} is the exergetic efficiency.
An evaluation of the economics of the installation of the plant was made including investment and operating costs for the Danish energy system Energinet.dk (2013). The specific investment of the vapor compression heat pump 0.57 MEUR per MW. For the absorption system it was 0.42 MEUR per MW. An average spot market electricity price of 28.67 EUR MWh^{-1} was used, while the heat price was 12 EUR MWh^{-1}.

3. RESULTS

3.1. Vapor Compression Heat Pump

The results of simulation of the plant at 100 % boiler load including the vapor compression heat pumps are illustrated in Figure 5. It was found that a heat pump of 83 MW capacity could be installed to reach 418 MJ s^{-1} combined district heating production. The heat pump used 17 MW and hence reached a COP of 4.87. This is based on a calculation for one single heat pump. In a practical installation the capacity of one unit would probably be lower, which would make it posssbile to take benefit of a serial connection of smaller heat pump units. By dividing the unit into 8 heat pumps of about 10 MW capacity, the COP would reach 5.38.
The extended operating map of the plant with the heat pump included is illustrated in Figure 6(a). It illustrates that the extended capacity will be available for all loads, and that the COP of the heat pump will be similar for the whole range. The difference in slope between the heat production based on steam extraction and heat pumping indicates that the heat pump is not able of utilizing the steam as efficiently as the extractions.

3.2. Absorption Heat Pump

For the absorption heat pump the analyses showed that the best option was to use the extraction at the lowest pressure taken from the feedwater tank or the IP2 turbine inlet. The results for this configuration at 100 % boiler load are illustrated in Figure 7. It was found that a heat pump capacity of 74.5 MW could be implemented reaching 375 MJ s^{-1} district heating production. The absorption heat pump COP was 1.75. The power sacrificed for the heat production was 8.9 MW, indicating an apparent COP of 8.4. The LiBr content of the strong solution was 62.6 %. For the weak solution it was 48.5 %. The low and high pressures of the heat pump were $0.20\,\text{bar}$ and $0.70\,\text{bar}$, respectively.
The extended operating map of the plant with the heat pump included is illustrated in Figure 6(b). The extended capacity will also for the absorption heat pump be available for all loads, and the COP of the heat pump will be similar for the whole range. Also in this case the difference in slope between the heat production based on steam extraction and heat pumping indicates that the heat pump is not capable of utilizing the steam as efficiently as the extractions. The map includes results for smaller heat pump capacity and hence glide as well. No significant difference in the performance was found for these configurations.

3.3. Comparison of performance

To evaluate the performance of the heat pump configurations a comparison to the plant operating in condensation mode and in back-pressure mode was developed.

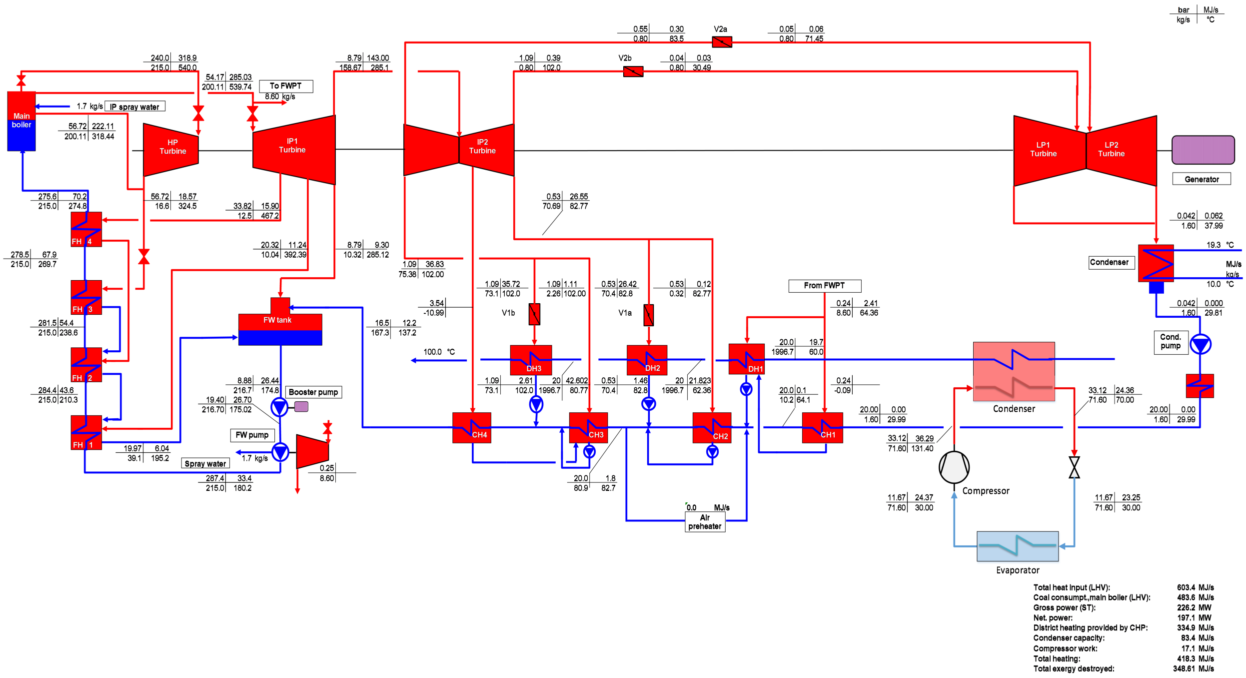
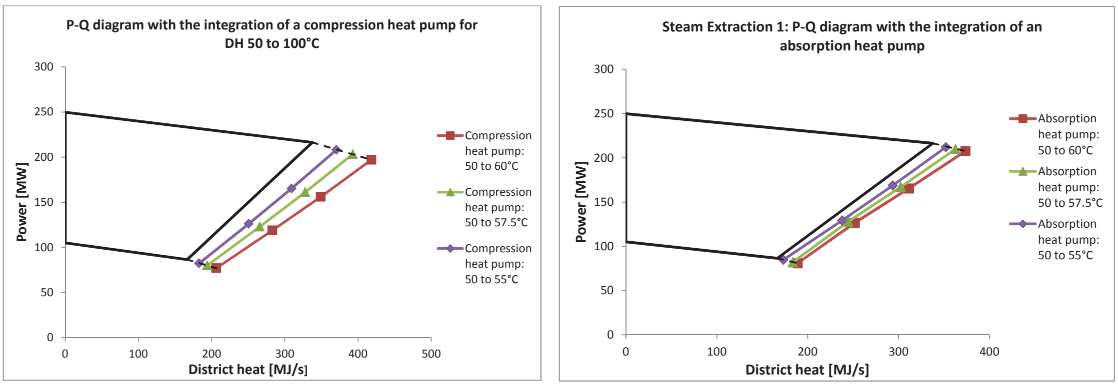


Figure 5. Process diagram for vapor compression heat pump integration



(a) Vapor compression heat pump (b) Absorption heat pump integration

Figure 6. Operating diagrams for heat pump integration

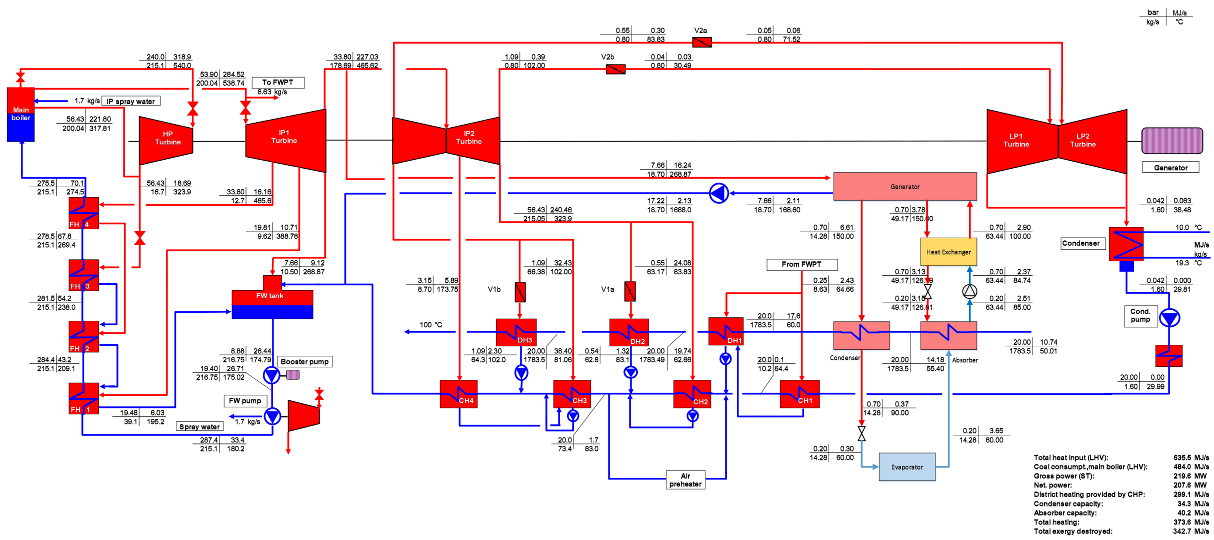
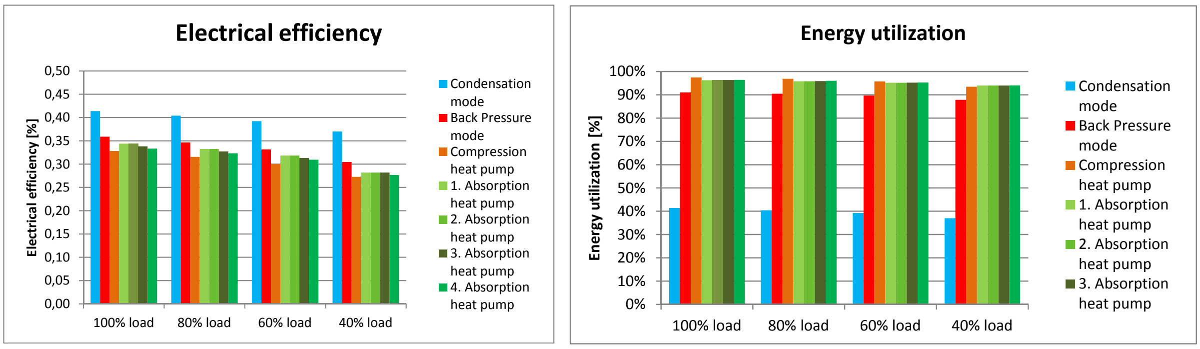


Figure 7. Process diagram for absorption heat pump integration



(a) Electrical efficiency (b) Energy utilization

Figure 8. Energy-based comparison of CHP plant and integrated configurations

Figure 8(a) shows the electrical efficiency of the plant in these two operating modes, and with the heat pumps included. This illustrates the higher efficiency resulting from pure power mode compared to operation which sacrifices power to produce heat. The heat pump configurations costed more power than the extraction mode, and the cost of heat pump configurations were similar. The higher efficiency when using the extraction presented in section 3.2 is also shown.

The electrical efficiency is to some extent of less importance, because the idea is to extend the heat production from the plant to be able to supply heat at high efficiency even if the power production may be less competitive in the future electricity market. The energy utilization resulting from the different configurations is illustrated in Figure 8(b). The considerable benefit from the combined production is obvious from this, showing that the back pressure mode reaches 91 % utilization at full load. The absorption heat pump integration reaches 96 % utilization, while the vapor compression unit reaches 97 % and is accordingly performing slightly better.

From a viewpoint of thermodynamics the exergetic performance provides a more reasonable comparison when the plant produces both power and heat of significantly different exergetic value. This is illustrated in Figure 9, which shows that all combined production modes showed lower exergy destruction than the condensation mode at 365 MW. The exergy destruction of the back-pressure mode was 339 MW, while it was 348 MW for the vapor compression cycle mode and 342 MW for absorption heat pump configuration.

The economic comparison of the two heat pump configurations show that the higher investment of the vapor compression unit has a significant impact on the economic feasibility. The absorption heat pump showed a payback period of 8.6 years, while it was 16.8 years for the vapor compression unit. These results seem quite reasonable for investment for a utility company, but they should be seen as initial estimates. Far more detailed analyses will be needed for an actual installation.

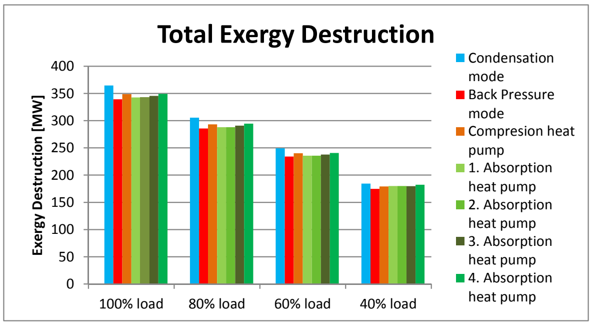


Figure 9. Total exergy destruction of CHP plant and integrated configurations

4. DISCUSSION

The analysis was made for two given heat pump configurations which fit well into the plant analyzed in the case. Other cases might show different results, e.g., for other district heating temperatures or for a plant with other steam conditions.

The aim of producing more heat from a CHP unit may also be solved by other means. For example bypassing some turbine stages by part of the steam and using it directly for heat production would be a simpler approach. However, it would not reach the same efficiency as is possible by the use of heat pumps.

For the absorption heat pump the evaporator temperature was assumed to be higher than for the vapor compression system. This was decided to avoid potential crystallization of the strong solution LiBr. The difference in performance was minor for variation of the evaporator temperature.

The approach of seeing a CHP plant as a virtual heat pump leads to the *additional fuel principle* for allocating fuel between heat and power production. The heat is a by-product and is seen to have the cost of the fuel used to generate the sacrificed power. Other methods of allocation may be applied which would lead to other costs of heat (Rambøll Danmark (2009)).

5. CONCLUSION

The study covers an analysis of a configuration of an advanced steam-based combined heat and power plant with focus on extending the heat production capacity of the plant by including vapor compression heat pumps and absorption heat pumps. The results showed that both types of heat pumps are able to extend the heat output of the plant at the cost of power production. The power is sacrificed either as electricity from the generator or as extraction steam from the intermediate pressure turbine. The potential for capacity expansion is to some extent limited due to the given configuration of the plant and the integration with the district heating system. Both types of heat pumps extends the heating capacity of the plant. The vapor compression unit produced 85.9 MJ s^{-1} additional heat at a COP of 4.9, hence costing 17.1 MW power. The absorption heat pump produced 74.5 MJ s^{-1} heat at a COP of 1.75, while sacrificing 8.9 MW power. The energy utilization is a little higher for the vapor compression unit, while the exergetic efficiency of the absorption heat pump is the highest. From an economic viewpoint the better efficiency and the lower investment of the absorption unit means that it will have a payback period of 8.6 years compared to 16.8 years for the vapor compression unit.

NOMENCLATURE

Abbreviations

CHP	Combined Heat and Power
COP	Coefficient of Performance

Latin symbols

$\dot{E}$	Exergy [MW]
$\dot{Q}$	Heat [MJ s^{-1}]
$\dot{W}$	Power [MW]

Greek symbols

η	Efficiency [–]

Subscripts

abs	Absorber
boiler	Boiler
comp	Compressor
cond	Condenser
dh	District heating
ex	Exergy
gen	Generator
net	Net

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